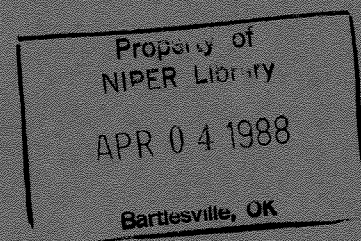


EVALUATION OF STEAM-TO-OXYGEN RATIOS FOR FORWARD COMBUSTION IN ASPHALT RIDGE TAR SAND

By
L. A. Johnson, Jr.
L. J. Romanowski, Jr.



August 1987

Work Performed Under Contract No. FC21-86MC11076

For
U. S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Laramie Project Office
Laramie, Wyoming

By
Western Research Institute
Laramie, Wyoming

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SUMMARY

Three one-dimensional and one three-dimensional physical simulations of forward combustion with steam-oxygen injection were conducted using Asphalt Ridge tar sand. One-dimensional simulations had steam-oxygen ratios of 3.1:1, 4.3:1, and 6.0:1 at oxygen fluxes of 10.8 to 8.0 scfh/ft². The three-dimensional simulation had a steam-to-oxygen ratio of 3.0:1.

Results from the one-dimensional simulations show a reduction in the fuel deposition and oxygen demand as the steam-to-oxygen ratio increases. In conjunction with reduction in fuel deposition is the increase in combustion front velocity and oil yield with increasing steam-to-oxygen ratio. These trends are assumed to be the result of improved displacement efficiency of the steam zone that precedes the pyrolysis and combustion zones in the forward combustion process and suppression of coking by the steam.

The effect of combustion front channeling was demonstrated by the three-dimensional simulation. Channeling caused a decrease in process sweep efficiency and oil yield with increased fuel consumption.

Product oil from all simulations were significantly improved in quality compared with the original bitumen. The product oils had significantly lower molecular weights, viscosities, and percentage of components boiling above 1000°F (538°C).

INTRODUCTION

The Asphalt Ridge tar sand deposit, located in the Uinta Basin of Utah, contains approximately one billion barrels of bitumen. The major bitumen saturation is found in the Rimrock sandstone of the Mesaverde group of Cretaceous Age. Average saturation for this deposit is 48% pore volume, at an average porosity of 27%. The low sulfur content bitumen has an in-place viscosity in excess of one million centipoise (IOCC 1984).

Preliminary laboratory studies of the applicability of wet- and dry-forward in situ combustion were conducted by Western Research Institute (Romanowski and Thomas 1986). The principal conclusions in this study were the following:

- Steam-oxygen combustion produced slightly greater oil yield and reduced fuel consumption and oxygen requirements.
- Steam injection with the oxygen reduced the coke deposition during pyrolysis, and the steam-char reaction further reduced the fuel available for combustion.
- The reduced fuel availability with steam injection increased the combustion front velocity by 44% compared with the front velocity with dry combustion.
- Both wet and dry combustion produced oil of higher quality in comparison with the original bitumen. However, produced oil from the steam-oxygen test was less improved in quality than the oil produced by dry combustion.

These observations are essentially the same as those given by other investigators (Burger and Sahuquet 1973; Bennion et al. 1978; Chu 1973) in studies of wet combustion in heavy oil and oil sands.

Based on the results of the above-mentioned study, a series of one-dimensional simulations followed by a three-dimensional simulation were designed to evaluate the effect of steam concentration on the steam-oxygen combustion process in Asphalt Ridge tar sand. The objectives of the simulations were (1) to determine the effect of oxygen-to-steam ratio on oil recovery, oxygen-to-fuel ratio, product gas and liquid qualities, and process temperature; and (2) to provide data for the validation of the predictive capability of the mathematical model for tar sand thermal processes. This report addresses the first of the two objectives.

EXPERIMENTAL APPARATUS AND PROCEDURE

The tar sand used in this study was obtained from an outcrop at the Asphalt Ridge deposit in Utah. This oil-wet tar sand had an average initial bitumen content of 13.5 wt %. with a water saturation of about 0.4 wt %.

Material balance Fischer assay analyses were conducted on three Asphalt Ridge outcrop samples to provide pyrolysis reference data for the forward combustion tests. During the Fischer assay procedure, the tar sand sample is heated autogenously at a rate of about 1300°F/hr (720°C/hr) to a maximum temperature of 932°F (500°C). At these pyrolysis conditions, the product oil has an atomic hydrogen-to-carbon (H/C) ratio of 1.71 and an API gravity of about 22°. The oil yield is 77 wt % with 19 wt % coke laydown.

One-Dimensional Simulations

The tube reactor used in the one-dimensional simulations (Figure 1) is capable of simulating the thermal recovery process of forward combustion, in addition to steam displacement, hot-gas pyrolysis, and reverse combustion. The reactor tube (3 5/16" i.d. x 32" long) is uniformly packed with approximately 18 lbs of tar sand (Romanowski and Thomas 1984) and is vertically oriented within a series of insulated shield heaters. Auxiliary equipment includes inlet gas injection and product gas metering devices, a steam generator, a gas heater, product separation equipment, a continuous oxygen analyzer, and a gas chromatograph. The entire system is instrumented and interfaced to a data acquisition computer that records temperatures, pressures, and flow rates every 5 minutes.

Six internal reactor thermocouples are spaced approximately every 6 inches within the center of the packed tar sand to monitor the thermal front movement. These thermocouples are also electronically paired with additional internal-wall thermocouples. Each pair is connected to one of six individual temperature controllers and shield heaters. This arrangement allows the reactor tube to be operated either isothermally (preheated) or adiabatically.

Steam and oxygen, either separately or simultaneously, are metered into the top of the reactor. A positive displacement pump injects water through a heater to generate steam.

Product oil and water samples are collected from three knockout pots. A constant reactor back pressure can be maintained by a flow control valve at the discharge port of the initial gas and liquid separator. The middle knockout pot is chilled to 32°F (0°C) to condense process water and oil vapors. A final cold trap is maintained at -94°F (-70°C) to recover entrained oil mist. Product gas volume is measured by a wet test meter and the gas composition is analyzed hourly by an on-line gas chromatograph. An on-line oxygen meter continuously monitors the oxygen concentration in the product gas to indicate rapid changes in the combustion process, such as those occurring during ignition.

Forward combustion experiments were initiated by using the guard heaters to raise the temperature of the packed sand to 250-300°F (121-149°C). When this temperature range was attained, injection of saturated steam at the rate to be used in the test was started to maintain a communication path through the tube. Once communication was confirmed, the top guard heater was raised to 650-700°F (343-377°C) and oxygen injection at the desired rate was established. At these

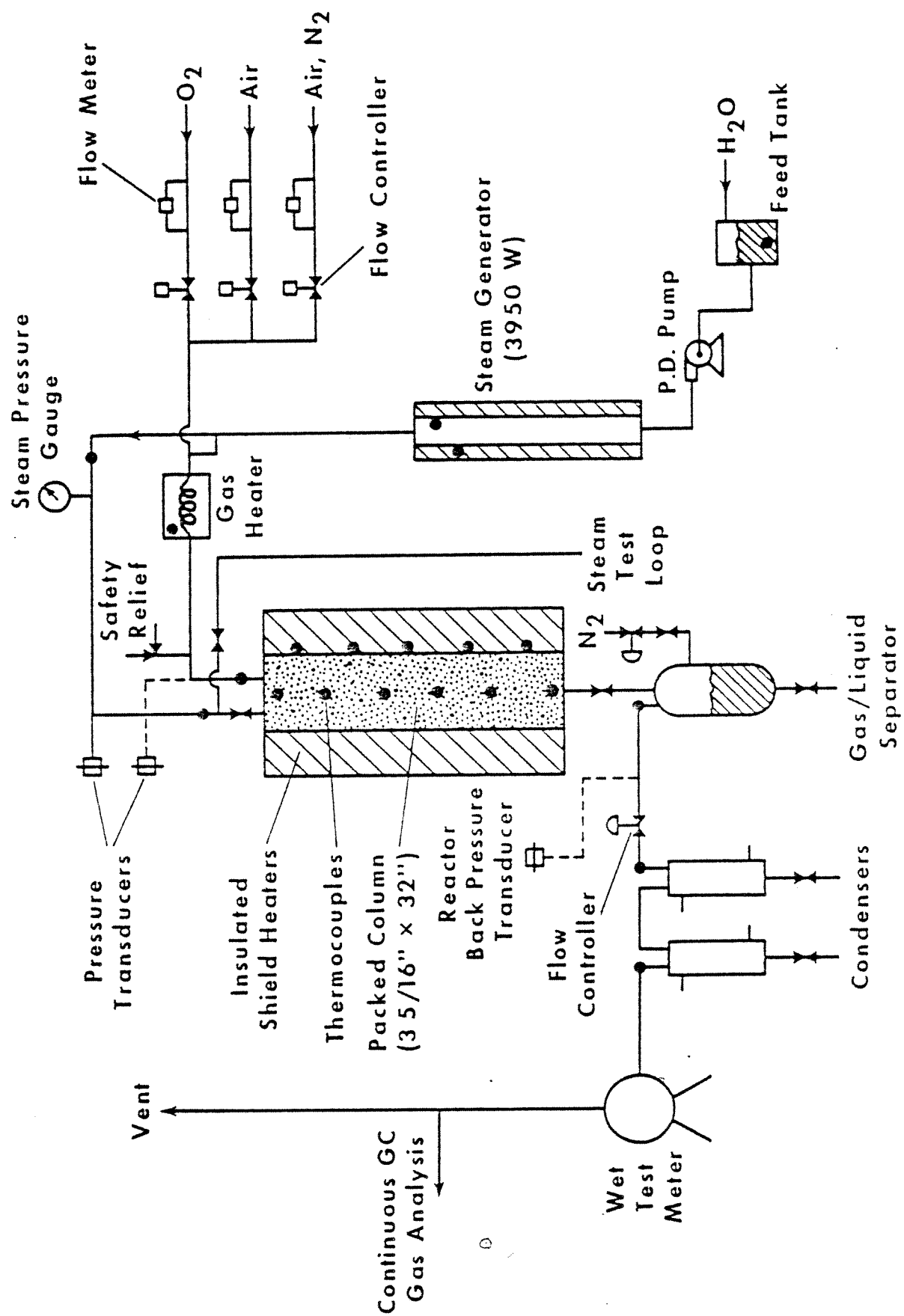


Figure 1. Tube Reactor Schematic

temperatures, the bitumen in the top 5-6 inches of the tar sand pack ignited and the oxygen in the product gas rapidly decreased to zero. Injection pressures at the time of ignition were generally less than 120 psig with no back pressure on the reactor. The experiments were terminated when combustion temperatures exceeded 500°F (260°C) at the bottom tar sand zone, or the oxygen content in the product gas exceeded 3 vol %, or oil production was negligible.

The spent tar sand was removed from the reactor tube, and the concentration of residual heavy oil and coke (toluene-insoluble organics) in the spent tar sand was measured. Sections representing each of the distinct process zones and approximately 25% of the total spent tar sand weight were analyzed. The residual heavy oil was determined by Soxhlet extraction with toluene. The coke was determined by difference after the extracted sample was burned in a muffle furnace at 900°F (482°C). The composition and volume of the product gas and the total organic carbon content of the product water were also measured for material balance calculations.

Three-Dimensional Simulation

The experimental apparatus used for this simulation is a unique and versatile high pressure reactor. The main component of the system is a large pressure vessel into which the encapsulated sample is placed. The pressure vessel is a thick-walled, horizontal, cylindrical unit 9 ft long and 6 ft in diameter. The vessel is sealed using 6-ft and 2-ft diameter screw-on domed ends (Figure 2). The reactor system is designed to operate at pressures up to 1000 psig.

Test samples as large as 2x2x2 ft are encased in a steel reaction box with high-temperature castable refractory. The reaction box is designed for placement of electrical heaters around the sample. Up to 80 thermocouples are installed in the sample and the encapsulating refractory.

The fluid handling system consists of an injection system, a product collection and sampling system, and a product gas flaring system. Injection capabilities include independent or co-injection of gases (air, nitrogen, carbon dioxide, steam, steam with air) at rates up to 35 scfm (85 lbs/hr steam) at 1000 psig and 900°F (482°C). Fluid production during the test can exit from up to seven production ports, depending on the injection-production scheme desired. At any one time, gas and liquid products from up to four of the production ports can be simultaneously monitored by passing the individual product streams through one of four parallel knockout pots where liquids are collected and measured. The gas is then combined and enters a gas cleanup system consisting of a series of heat exchangers, knockout pots, filters and a demister. Following cleanup, the flow volume is measured and the clean gas analyzed by an on-line gas chromatograph.

The reactor instrumentation and control system is a highly integrated network of flow controllers and meters, pressure regulators and transmitters, microprocessors, recorders, thermocouples, gas analysis equipment, and a minicomputer for data collection, storage, and

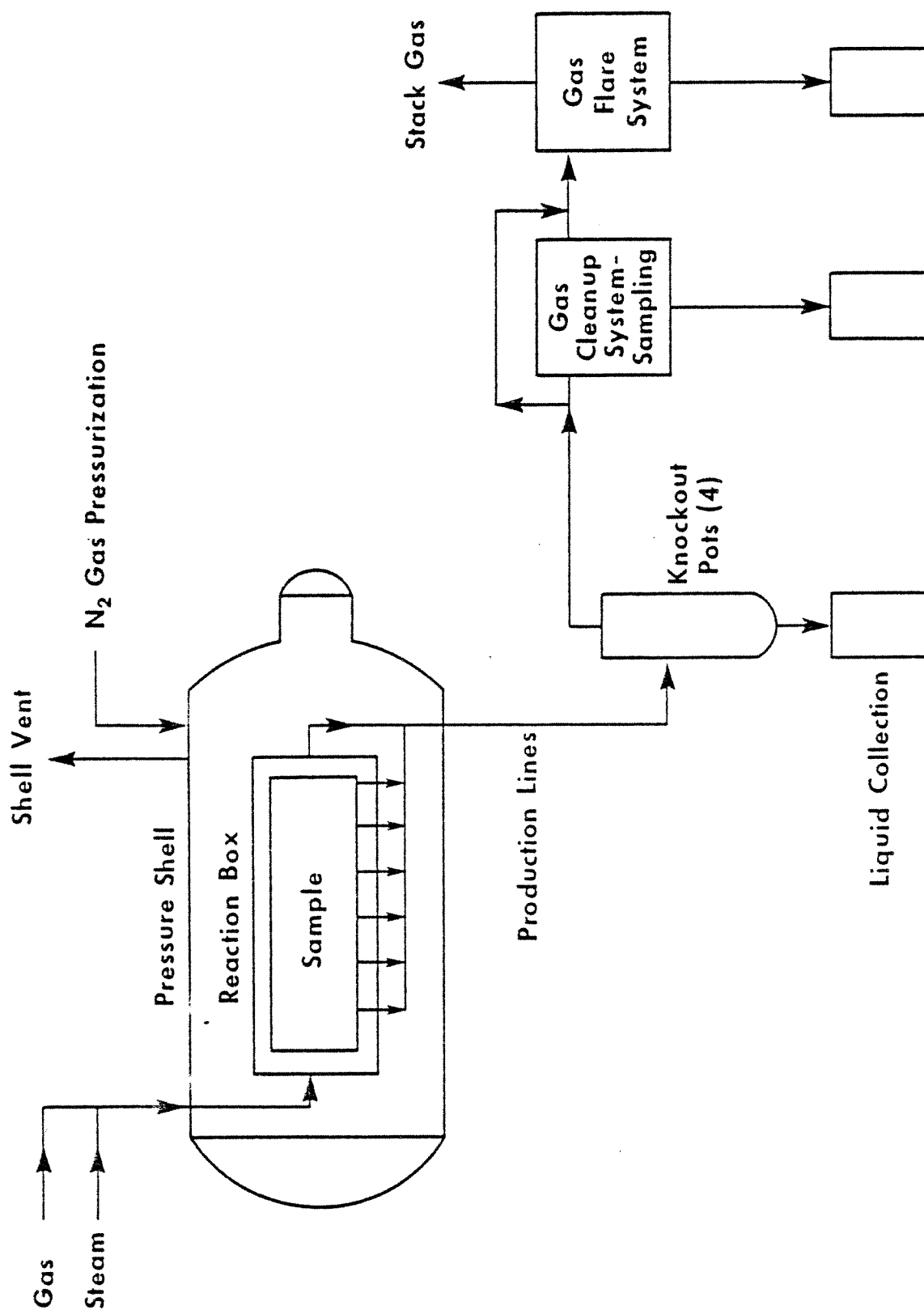


Figure 2. Block Reactor Schematic

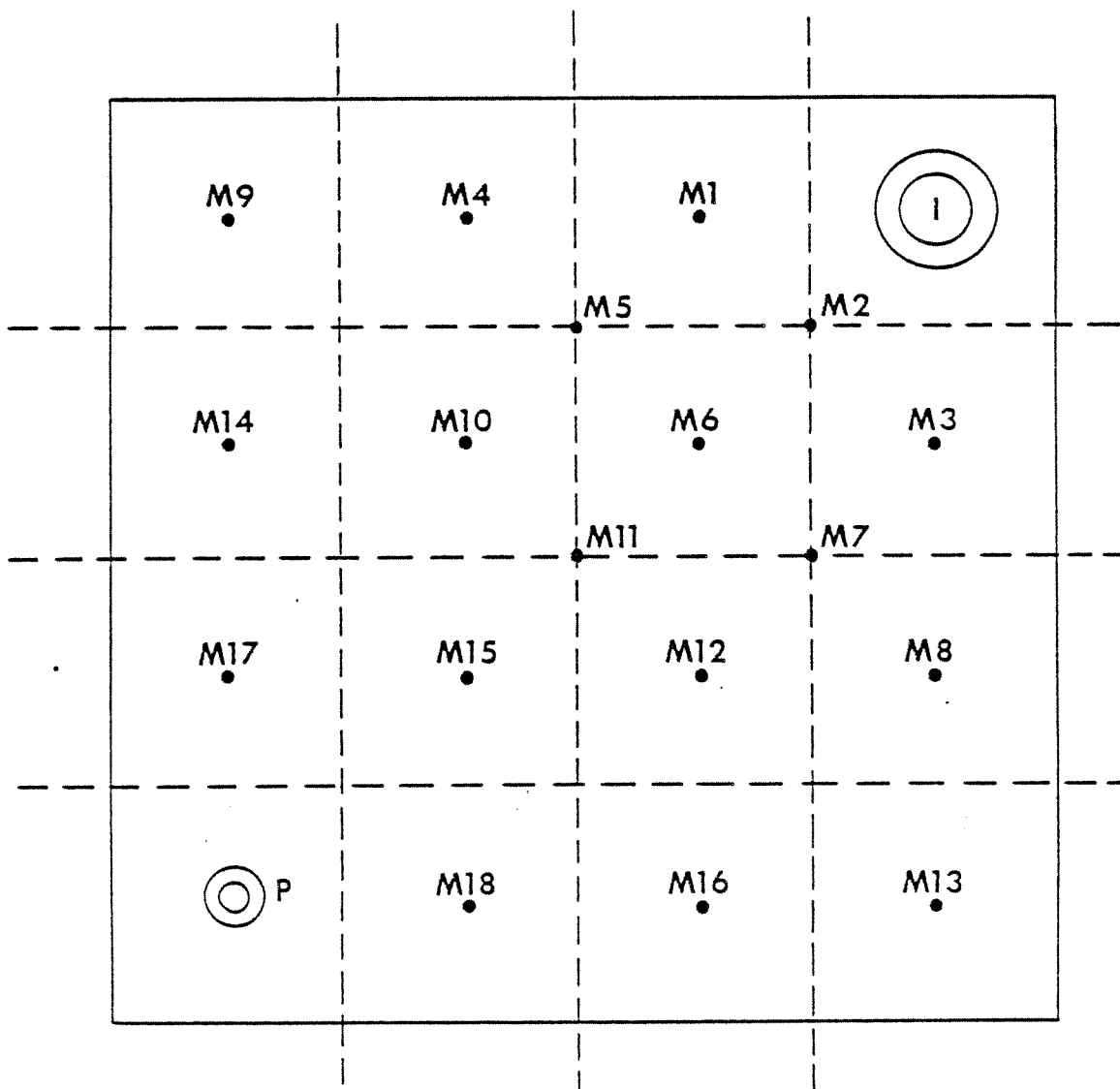
analysis. All thermocouple, pressure, and flow data are recorded every 5 minutes by the computer for both real-time and end-of-test analysis.

For this simulation, a block had to be reconstructed from crushed tar sand material. To produce the block, 24 increments of the tar sand material were packed into a 2x2x1-ft frame. A bulk density equal to that of the one-dimensional simulations was maintained. The block was then completed with a production and injection well to represent a quarter of a five-spot well pattern and 18 temperature monitoring wells (Figure 3). Thermocouple locations within each monitor well are given in Table 1. To complete sample preparation, guard heaters were placed 3/4 inch above and below the block and an ignition heater was sand packed into the injection well.

To initiate the simulation, the guard heaters were activated to raise the temperature of the block to 200 to 250°F (93 to 121°C). With the majority of the block at the preheat temperature, the ignition heater was activated at the same time that air injection was established. A flux of 80 to 120 scfh/ft², 3 inches from the wellbore, was used. Air injection was then continued until the temperature in the first ring of temperature wells reached 600-800°F (315-427°C), indicating establishment of a high-temperature combustion front. Oxygen was then added to the injectant stream as the air rate was decreased such that the oxygen content in the injectant was 35% by volume. This injection scheme was continued until there was complete oxygen utilization and temperatures reached 1000°F+ (538°C+) in the first ring of monitor wells.

With the indication of a vigorous combustion front, complete oxygen utilization and 1000°F+ (538°C+) temperatures, the injectant stream was changed from air-oxygen to steam-oxygen at a steam-to-oxygen ratio of 3.0:1. This steam-to-oxygen ratio was then used throughout the test by adjusting the oxygen and steam rates to maintain fluxes of approximately 8 and 24 scfh/ft², respectively, at the 900°F (482°C) isotherm. The 900°F (482°C) isotherm was a three-dimensional representation of the combustion front determined from the monitor well temperatures. Oxidant injection continued until 600°F+ (315°C+) temperatures were observed in the temperature monitor wells nearest the production well. This termination criterion was set to prevent burning of the product oil in the production well bore and lines. Following oxidant termination, nitrogen was injected to displace any combustion gas or product liquids from the production lines and to cool the block.

After cooling of the block, the reaction box was opened and the spent material sampled. Sampling of the material consisted of removing the sample in six layers with measurements and weights being recorded for the combusted sand, coke, steamed and unreacted zones. Samples from each zone in each layer were taken for measurement of coke, water, and residual oil for material balance calculations.



I Injection Well

P Production Well

M Monitor Well (See Table 1 for Thermocouple Locations)

Figure 3. Well Locations for the Asphalt Ridge Three-Dimensional Steam-Oxygen Forward-Combustion Simulation

Table 1. Location of Thermocouples in Three-Dimensional
Sample for Asphalt Ridge Steam-Oxygen Forward
Combustion Simulation

Monitor Well	Thermocouple Number	Depth from Top of Block, inches
M1	201	3
	202	6
	203	9
M2	204	3
	205	6
	206	9
M3	207	3
	208	6
	209	9
M4	215	4
	216	8
M5	213	4
	214	8
M6	210	3
	211	6
	212	9
M7	231	4
	232	8
M8	236	4
	237	8
M9	220	6
M10	217	3
	218	6
	219	9
M11	228	3
	229	6
	230	9
M12	233	3
	234	6
	235	9
M13	238	6
M14	221	4
	222	8
M15	225	3
	226	6
	227	9
M16	239	4
	240	8
M17	223	4
	224	8
M18	301	4
	302	8

Product Samples

Product liquid samples from both the one- and three-dimensional tests were separated into oil and water by centrifugation or the azeotropic separation with benzene or methylene chloride. A sample of the original bitumen from the untreated tar sand was also obtained by Soxhlet extraction with toluene and pyridine.

Selected chemical and physical properties of the bitumen and product oils were determined by ASTM procedures. Analyses included specific gravity, viscosity, molecular weight, distillation range and elemental analysis for carbon, hydrogen, nitrogen, and sulfur. These analyses along with a mineral carbon analysis of the raw tar sand provide data for material and elemental balances and product upgrading determinations.

RESULTS AND DISCUSSION

One-Dimensional Simulations

The three one-dimensional simulations (FC60, FC61, and FC62) were conducted at steam-to-oxygen ratios of 3.1:1, 4.3:1, and 6.0:1, and oxygen fluxes of 10.8, 8.6, and 8.0 scfh/ft² (Table 2). Ignition was established between 650 and 750°F (343-399°C) in all simulations and the combustion front was successfully propagated through the tar sand bed.

The injection pressure histories for all simulations were similar, varying only in magnitude. At the time of ignition, pressure ranged from 60 psig in FC60 to 120 psig in FC62. However, as the combustion fronts advanced, the injection pressure rapidly increased to the maximum pressure observed for each simulation. Maximum injection pressures ranged from 630 psig for FC60, the lowest steam-to-oxygen ratio, to 400 psig for FC62, the highest steam-to-oxygen ratio. This pressure difference indicates that the higher steam fluxes maintained more permeable communication channels during the simulations. The higher steam fluxes transported more heat from the region behind and in the combustion zone to the cooler region ahead of the combustion zone. Injection pressures remained high for a period of time and then decreased as rapidly as they increased. During the high pressure period for all three tests, between 25 and 40% of the total product oil was produced. Viscosity of this produced oil was an order of magnitude higher than other oils produced during the test, indicating a relatively high concentration of essentially unaltered bitumen. The injection pressure then began to increase to a pressure less than the initial high pressure and remained nearly constant for the remainder of the simulation. The shape of the pressure curve for FC62 (Figure 4) is typical for all three simulations.

The peak combustion temperatures for FC60 and FC62 ranged from 1200 to 1500°F (649 to 816°C) while the temperature for FC61 ranged from 1350 to 1600°F (732 to 871°C). The higher temperatures in FC61 are attributed to the improper functioning of the guard heaters, which ultimately drove the temperatures in the simulation to 1700-1800°F (927-982°C) after the combustion peaks were attained. As discussed later, these higher,

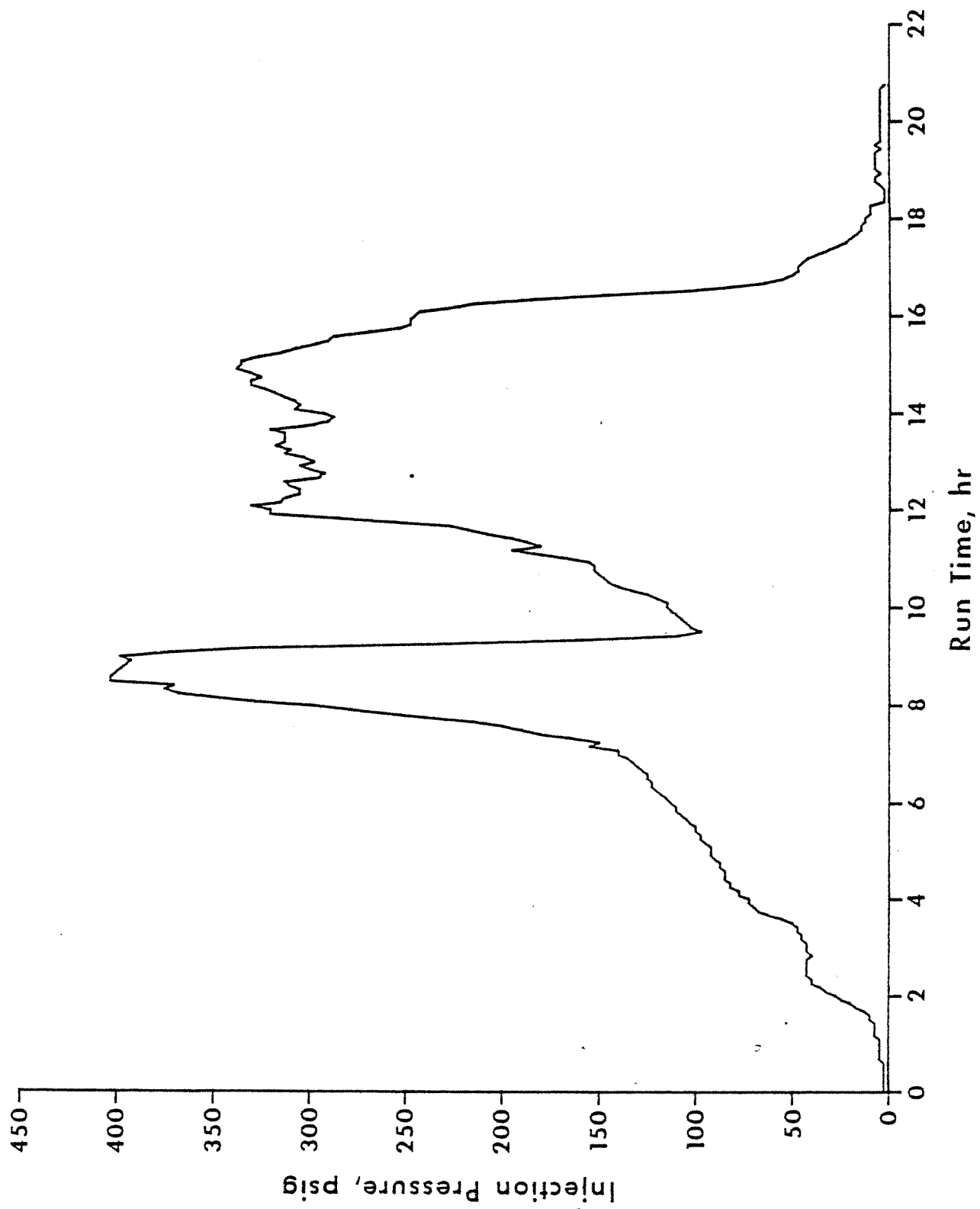


Figure 4. Injection Pressure Profile for Asphalt Ridge Test FC62

Table 2. Experimental Conditions and Results for
Asphalt Ridge Steam-Oxygen Combustion Tests

	FC60	FC61	FC62	BR16
Permeability, darcy	1.2	1.1	1.6	--
Porosity, %	40	38	40	36
Oil Saturation, % PV	62	66	61	73
Injected Flux, scfh/ft ²				
Steam	34	37	48	--
Oxygen	10.8	8.6	8.0	--
Steam-to-Oxygen Ratio	3.1:1	4.3:1	6.0:1	3.0:1
Steam Preheat, PV	0.087	0.133	0.140	0
Cumulative Co-Injection				
Steam, PV	0.29	0.40	0.53	0.38
Oxygen, scf	7.46	7.02	5.40	254
Maximum Injection Pressure, psig	630	450	400	670
Peak Combustion Temperature, °F	1200-1500	1350-1600 ^a	1300	1000-1700
Combustion Front Velocity, ft/day	4.3	3.5	5.4	5.0-20.0
Fuel Deposition				
wt % Initial Bitumen	10.9	12.8	9.2	56.9 ^b
lb/ft ³ Tar Sand	1.7	2.1	1.4	9.5 ^b
Oil Yield				
wt % Initial Bitumen	80.3	80.1	90.1	41.3 ^b
% OOIP	82.7	82.2	93.0	42.4 ^b
wt % Fischer Assay	97.2	97.0	109.0	50.0 ^b

^a Maximum temperatures observed were 1700-1800°F because of controller overriding.

^b Based on sweep area

artificially achieved temperatures had an influence on the test results. The shape of the temperature profiles, represented by those for FC62 in Figure 5, as the combustion front moved down the tubes is similar to those given by several other investigators. The similar combustion temperatures for FC60 and FC62 were expected since other investigators (Shu and Lu 1983) have reported similar temperatures when burning similar reservoir materials at the same oxygen flux.

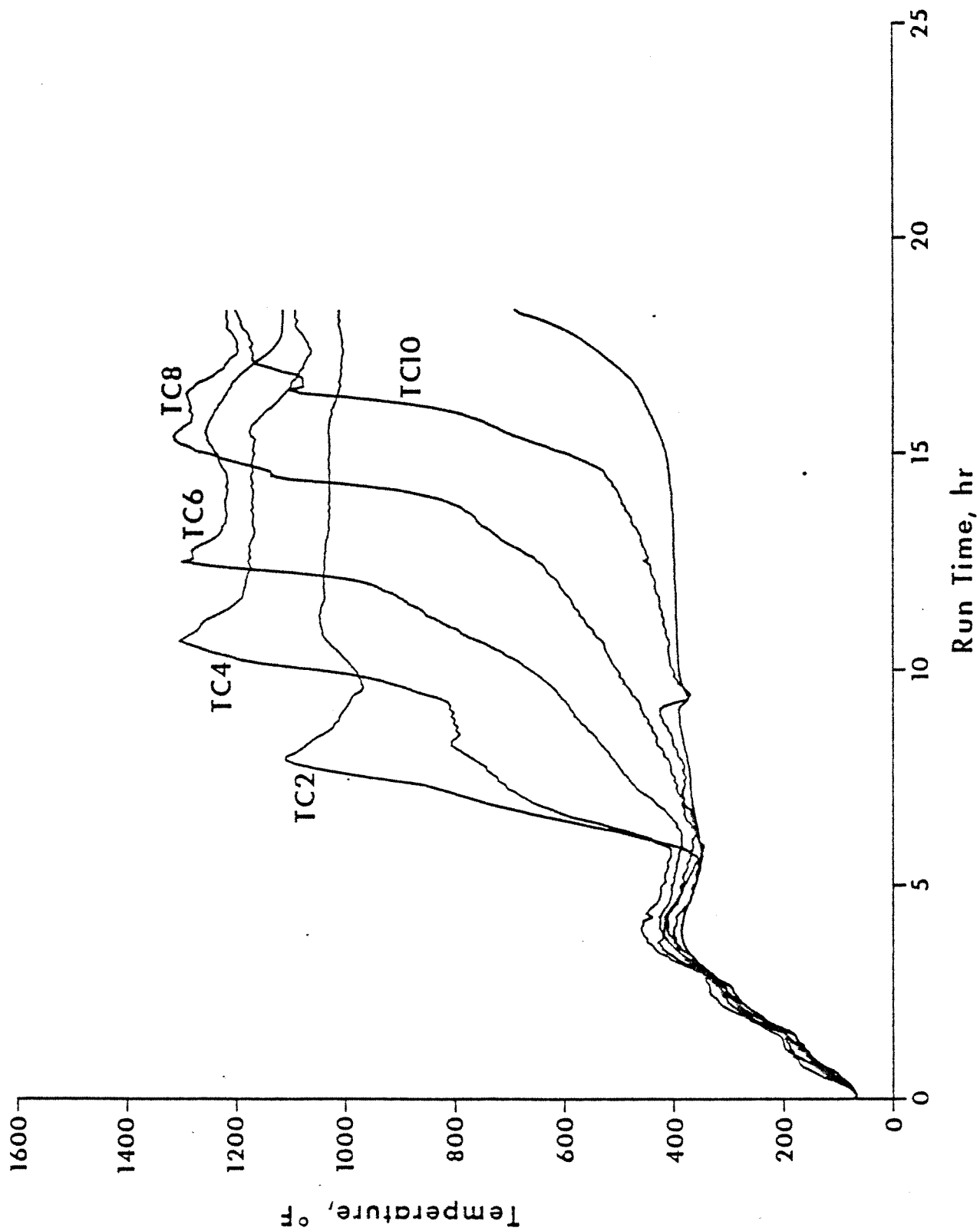


Figure 5. Temperature Profiles for Asphalt Ridge Test FC62

The product gas composition for the simulations (Table 3) showed high concentrations of carbon dioxide, which is a characteristic of oxygen firefloods. The increase in hydrogen sulfide content as the steam-to-oxygen ratio increased was expected because of increased aquathermolysis with increasing steam flux. Overall, the gas composition for FC60 and FC62 were very similar. Both contained the same relative percentage of pyrolysis gas as indicated by the methane content. Increased hydrogen content in FC62 compared with FC60 resulted from an increase in the steam-char reaction with increased steam partial pressure.

Table 3. Product Gas Composition (Dry Basis) from Asphalt Ridge Steam-Oxygen Combustion Tests

	FC60	FC61	FC62	BR16 ^a
Injected Gas Flux, scfh/ft ²	45	46	56	
Steam-Oxygen Ratio	3.1:1	4.3:1	6.0:1	3.0:1
Product Gas Composition, vol %				
H ₂	2.5	19.3	4.5	2.7
O ₂	0.0	0.0	0.0	0.3
CO	6.6	3.2	4.9	7.1
CO ₂	79.7	63.5	77.2	72.9
CH ₄	5.7	7.2	5.4	9.6
C ₂ =	1.1	1.0	1.0	2.0
C ₂	0.3	0.1	0.1	0.9
C ₃ =	0.5	0.3	0.3	1.4
C ₃	0.9	0.7	0.6	1.1
C ₄ +	0.8	0.4	0.6	1.5
H ₂ S	1.9	4.3	5.4	0.5

^a Nitrogen- and argon-free basis

Gas composition for FC61 differed from those for FC60 and FC62 because of the higher temperatures generated in the tube by the guard heaters. It is postulated that in generating the higher process temperatures in FC61, the guard heaters also produced a differential temperature gradient across the cross section of the tube. Therefore, the higher wall temperatures would have restricted the gas flow along

the edge of the tar sand bed, producing inadequate sweep of products from the area. The insufficient sweep permitted secondary coking to occur as a liquid-phase reaction which consumed both bitumen and pyrolysis products. This secondary coking resulted in the higher concentrations of hydrogen and methane in the product gas (Table 3). Additional effects of secondary coking on other test results are discussed later.

The fuel deposition during the simulations ranged from 12.8 wt % of the initial bitumen in FC61 to 9.2 wt % in FC62 based on the nonpyrolysis-produced carbon monoxide, carbon dioxide, and hydrogen in the produced gas, the excess product water, and the residual coke on the spent sand. But if the fuel deposition of FC61 were based on a linear interpolation of FC60 and FC62, then it would be 10.2 wt % instead of 12.8 wt %. The additional 2.6 wt % fuel deposition, a 25% increase, indicates the extent to which secondary coking influenced the simulation. Comparison of FC60 and FC62 indicates that fuel laydown decreased as the steam-to-oxygen ratio, and therefore the steam concentration, increased. The higher steam concentration both improves the displacement efficiency of the process by removing a larger portion of the bitumen from the reaction tube before it is pyrolyzed to produce coke and increases suppression of coking by the steam (Monin and Audibert 1985). Also, the fact that the fuel deposition in FC60 and FC62 was significantly less than the 12.5 wt % coke produced by strictly pyrolyzing the bitumen (Turner and Nickerson 1986) indicates that some bitumen was displaced before pyrolysis.

Since the velocity of a flame front is inversely proportional to the amount of fuel deposited less fuel consumed by the steam-char reaction, the combustion front velocity should have increased from FC60 to FC62 (Prats 1982). This trend was observed with the velocity increasing from 4.3 ft/day for FC60 to 5.4 ft/day for FC62. The velocity for FC61, 3.5 ft/day, also followed this trend. However, FC61 did not follow the trend of increasing velocity with increasing steam-to-oxygen ratio. The excessive fuel deposition prevented that occurrence. The combustion front velocity for FC61 based on a linear extrapolation of steam-to-oxygen ratio versus frontal velocity data for FC60 and FC62 was estimated to be 4.75 ft/day. The difference between the estimated and observed frontal velocities was 26%, which is essentially the same percentage difference as that for the interpolated and observed fuel depositions. This close agreement is consistent with the assumed linear relationships between the steam-to-oxygen ratio and fuel laydown and frontal velocity for a given hydrocarbon and similar oxygen flux.

Comparing the frontal velocity of FC61 with that of 5.4 ft/day for an earlier simulation (FC59) (Romanowski and Thomas 1986) shows what appears to be a significant difference even though both simulations used the same resource, had a similar steam-to-oxygen ratio, 4.3:1 and 4.0:1 respectively, and guard heater functioning. However, if the difference in initial bitumen content (13.5 versus 10.2 wt %) and the higher average system operating pressure (300 versus 120 psig) of FC61 are analyzed in relation to the fuel laydown trends reported by Alexander et al. (1962) and Showalter (1963), the predicted velocity of FC61 would be

3.6 instead of the observed 3.5 ft/day. This comparison shows that (1) increases in system pressure and initial bitumen content increase fuel deposition and therefore decrease frontal velocity, and (2) results from simulations using this reactor system are consistent and therefore can be used with confidence for making future predictions.

Four material balances were performed on each simulation. The overall material balances for the one-dimensional tests averaged 98.4% (Table 4), while the carbon balance had a slightly lower average, 97.7% (Table 5). Oxygen and hydrogen balances, not presented, averaged 93.6 and 97.8%, respectively. The high average closure of all balances gave confidence in the simulation results.

**Table 4. Overall Material Balances for Asphalt Ridge
Steam-Oxygen Combustion Experiments**

	FC60	FC61	FC62	BR16
<u>In, gram</u>				
Tar Sand	8087	8261	8153	233256
Bitumen	1092	1115	1101	31723
Water	33	34	33	933
Sand	6962	7112	7019	200600
Oxygen	285	269	206	9702
Air	0	0	0	10379
Steam	<u>647</u>	<u>876</u>	<u>938</u>	<u>16151</u>
Total In	9019	9406	9287	269488
<u>Out, gram</u>				
Product Oil	877	893	992	4194
Residual Oil	13	5	1	17991
Residual Coke	15	35	18	1631
Spent Sand	6857	6966	6875	196796
Product Water	748	898	1033	13150
Water on Sand	2	1	2	1015
Water in Gas	4	4	3	314
Product Gas	<u>360</u>	<u>377</u>	<u>290</u>	<u>24165</u>
Total Out	8876	9179	9214	259256
Total Closure, %	98.4	97.6	99.2	96.2
Sand Closure, %	98.5	97.9	97.9	98.1
Water Closure, %	110.1	99.2	106.9	84.8

Table 5. Carbon Balances for Asphalt Ridge
Steam-Oxygen Combustion Experiments

	FC60	FC61	FC62	BR16
<u>In, gram</u>				
Bitumen	<u>937</u>	<u>957</u>	<u>945</u>	<u>27,218</u>
Total In	937	957	945	27,218
<u>Out, gram</u>				
Product Oil	754.8	771.7	863.6	3,623
Residual Oil	11.2	4.3	0.8	14,637
Residual Coke	13.5	31.8	15.8	2,167
Product Water	1.0	1.0	1.0	32
Product Gas	<u>105.3</u>	<u>97.5</u>	<u>73.0</u>	<u>6,863</u>
Total Out	885.8	906.3	954.2	27,322
Balance Closure, %	94.5	97.7	101.0	100.3

Oil yield for the simulations was consistently high, ranging from 80.1 and 80.3 wt % of initial bitumen in FC61 and FC60 to 90.1 wt % in FC62 (Table 2). The anticipated trend of increasing oil yield with increasing steam-to-oxygen ratio was observed in FC60 and FC62. Oil yield for FC61 did not follow this trend because of the higher fuel deposition caused by the secondary coking. The linear interpolated oil yield for FC61, based on yields from FC60 and FC62, was 85.2 wt %. Consequently, about 6% of the potential liquid hydrocarbon product must have been subjected to secondary coking or combusted. The volumetric oil yields were slightly higher, 82.2 to 93.0% OOIP, than the weight percentage of oil recovery because of the upgraded condition of the product oil. Comparison of the oil yields with the 82.6 wt % oil yield produced exclusively by pyrolysis (Turner and Nickerson 1986) shows recoveries of 97.0 to 109.0 wt % of pyrolysis yield. These high oil recoveries were, as previously mentioned, because a portion of the bitumen was displaced before it could be pyrolyzed to form coke.

The product oils from the three one-dimensional simulations were all upgraded compared with the initial bitumen (Table 6). The product oils had lower molecular weights, percentage residual compounds (compounds with >1000°F [538°C] boiling point), and viscosities than the initial bitumen. API gravity for the product oils ranged from 14.1° to 15.0° compared with 10.2° for the original bitumen. The FC61 product oil showed less upgrading than the oils from FC60 and FC62. Secondary coking in FC61 produced a heavier oil by elimination of hydrogen and methane and rejection of residual carbon. This heavier oil tended to reduce the quality, mainly viscosity, of the pyrolysis-produced oil.

Table 6. Chemical and Physical Properties of Original Bitumen and Produced Oils (Asphalt Ridge)

	Bitumen	FC60	FC61	FC62	BR16
Elemental Analysis, wt %					
Carbon	85.8	86.1	86.0	86.5	86.4
Hydrogen	11.5	11.9	12.0	11.9	11.6
Nitrogen	1.1	1.4	1.4	1.0	1.1
Sulfur	0.4	0.6	0.6	0.6	1.3
Oxygen (by difference)	1.2	TR	TR	TR	--
H/C Ratio	1.61	1.66	1.67	1.65	1.61
Molecular Weight	670-710	460	510	450	320
Gravity, °API	10.4	14.5	14.1	15.0	16.0
60/60°F	0.997	0.969	0.972	0.966	0.959
Distillation Data, wt %					
0-600°F	5.2	14.0	13.7	13.9	36.9
600-1000°F	34.7	38.4	40.2	37.9	50.3
>1000°F	60.1	47.6	46.1	48.2	12.8
Viscosity, cp					
60°F	--	166,000	--	--	--
100°F	--	10,700	21,800	7,270	134
140°F	59,000	940	2,200	1,040	41
195°F	--	--	270	--	--

Note: Properties for FC60, FC61, and FC62 produced oil are the weighted average for all samples collected during the simulation except viscosity and molecular weight, which were determined by an Arrhenius-type mixing rule.

Comparing the product oil properties from these simulations with the oil properties given by Romanowski and Thomas (1986) for air and steam-to-oxygen combustion of Asphalt Ridge tar sand indicates that a higher percentage of bitumen was produced during these simulations. This difference in oil quality was not unexpected since the initial saturation in these simulations, 13.5 wt %, was higher than the 10.2 and 11.2 wt % tar sand used in the aforementioned study. The higher oil saturation provides more bitumen for displacement. Comparison of the product oil properties with the oil properties of an isothermally produced pyrolysis oil (Turner and Nickerson 1986) also shows that bitumen and possibly partially pyrolyzed oil were produced. The higher molecular weight (450-510 versus 280), the lower H/C ratio (1.65-1.67 versus 1.82), and the lower percentage hydrogen (11.9-12.0 versus 12.6) of the product oils all indicate that dilution of the pyrolysis-produced oil by the heavier components occurred.

Three-Dimensional Simulations

The three-dimensional simulation, BR16, was preheated for 6 hours by electrical preheat with a 0.5 scfm sweep of nitrogen gas. Ignition was accomplished by switching from nitrogen to 1.15 scfm of air with the wellbore heater activated. Temperatures in the monitor wells were 200-300°F (93-149°C) and the injection pressure (Figure 6) was 30 psig at this time. Injection rate and pressure remained constant until oxygen at 0.6 lb/hr was introduced into the injectant stream. The pressure then steadily increased to approximately 400 psig at which point air injection was terminated and steam injection initiated. During the steam-to-oxygen co-injection period, the injection pressure steadily increased from approximately 400 psig to a maximum of 670 psig (Table 2) as the total injection was increased to maintain an approximate flux of 40 scfh/ft² at the 900°F (482°C) isotherm. The steam-to-oxygen ratio during this period averaged 3.0:1. During the final 5 hours of the test, the injection pressure rapidly decreased to 440 psig at which point the test was terminated because of excessive temperatures at the production well.

The peak combustion temperatures for the thermocouple locations nearest the injection well, monitor well 2 (Figure 7), were approximately 1000°F (538°C) and were used as the indicators for starting oxygen injection. The vertical combustion front then moved rapidly down the line of monitor wells between the injection and production wells (Figures 8 and 9) to produce a heated channel between the process wells. Peak temperatures during this enriched air period with its rapidly advancing combustion front ranged from 1000 to 1700°F (538 to 927°C).

Following the start of steam injection, the combustion front stagnated between monitor wells 11 and 15. It is postulated that the steam began to move bitumen from the edges of and into the heated channel. This movement of steam-displaced oil into the combusted region is indicated by the secondary and tertiary temperature peaks shown in Figure 7, 8, and 9 and continued throughout the steam-oxygen injection period.

The volumetric sweep of the combustion simulation was 26.1% for the combusted zone with an additional 6.0% for the pyrolysis zone (Figure 10). This 32.1% total sweep is well below the theoretical 50% sweep of an unconfined five-spot pattern. The lower sweep was caused by the rapid growth of a channel between the injection well and production, which limited the areal extent of the sweep zone. The rapid advance of the combustion front between the injection is shown by the average velocity, which increased from 5.0 ft/day between monitor wells M2 and M6 to approximately 20 ft/day from M6 to M11. The front velocity then decreased drastically between M11 and M15 as steam was added to the system.

The average gas composition for the three-dimensional simulation is given on a nitrogen- and argon-free basis in Table 3. The higher content of hydrocarbon gases in BR16 than in the one-dimensional simulations indicates that secondary cracking of the product oil

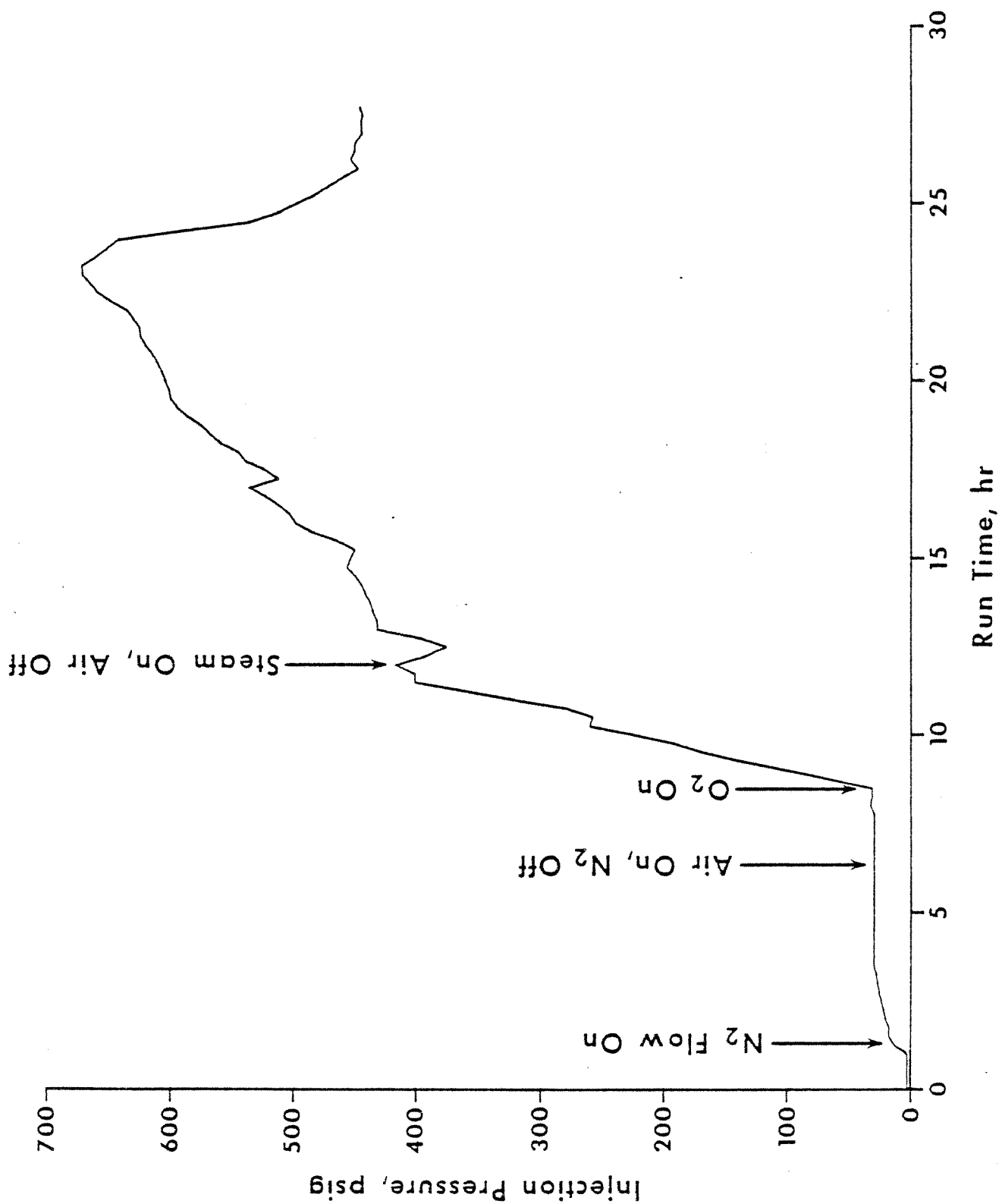


Figure 6. Injection Pressure for Asphalt Ridge Test BR16

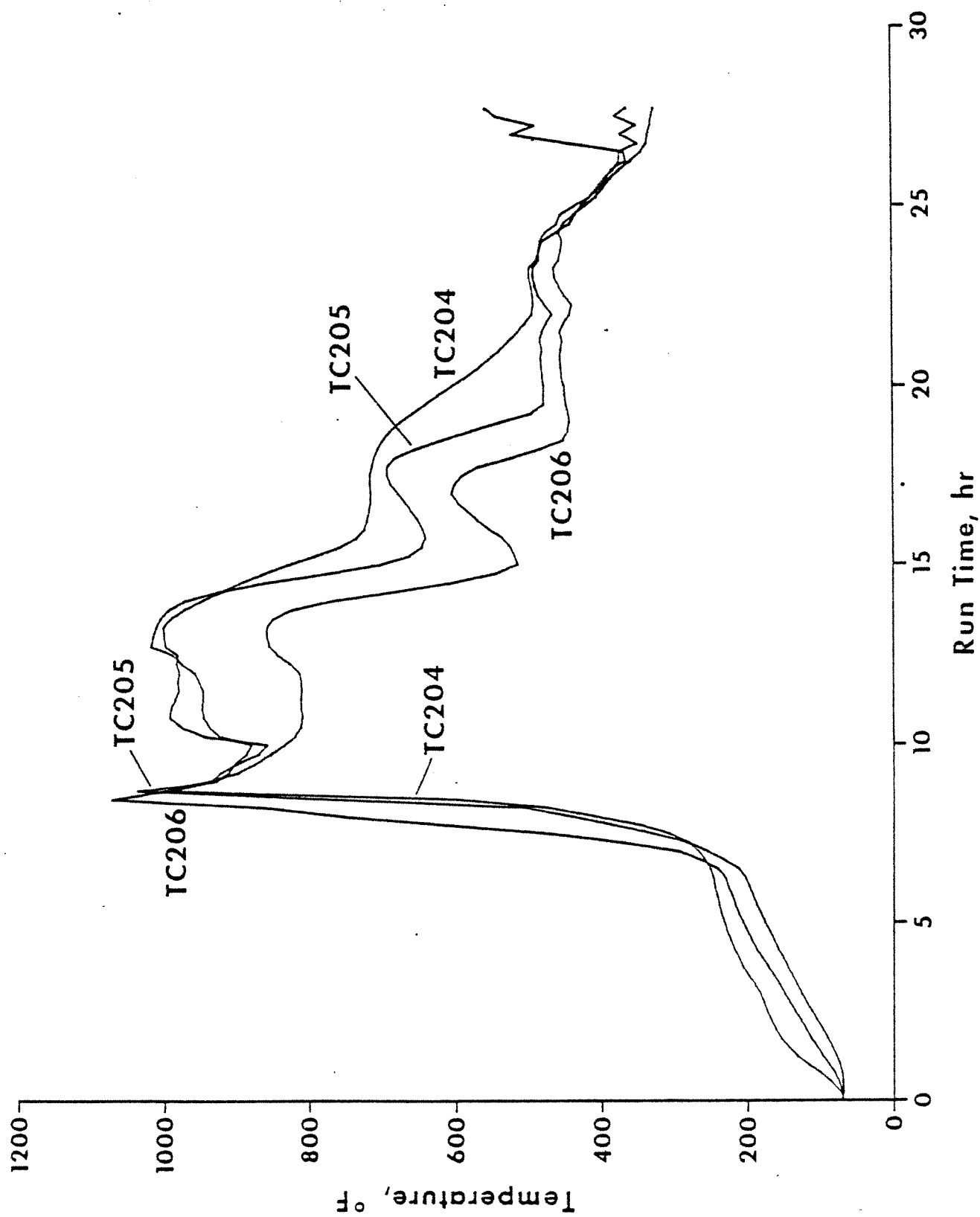


Figure 7. Process Temperatures for Asphalt Ridge Test BR16, Well M2

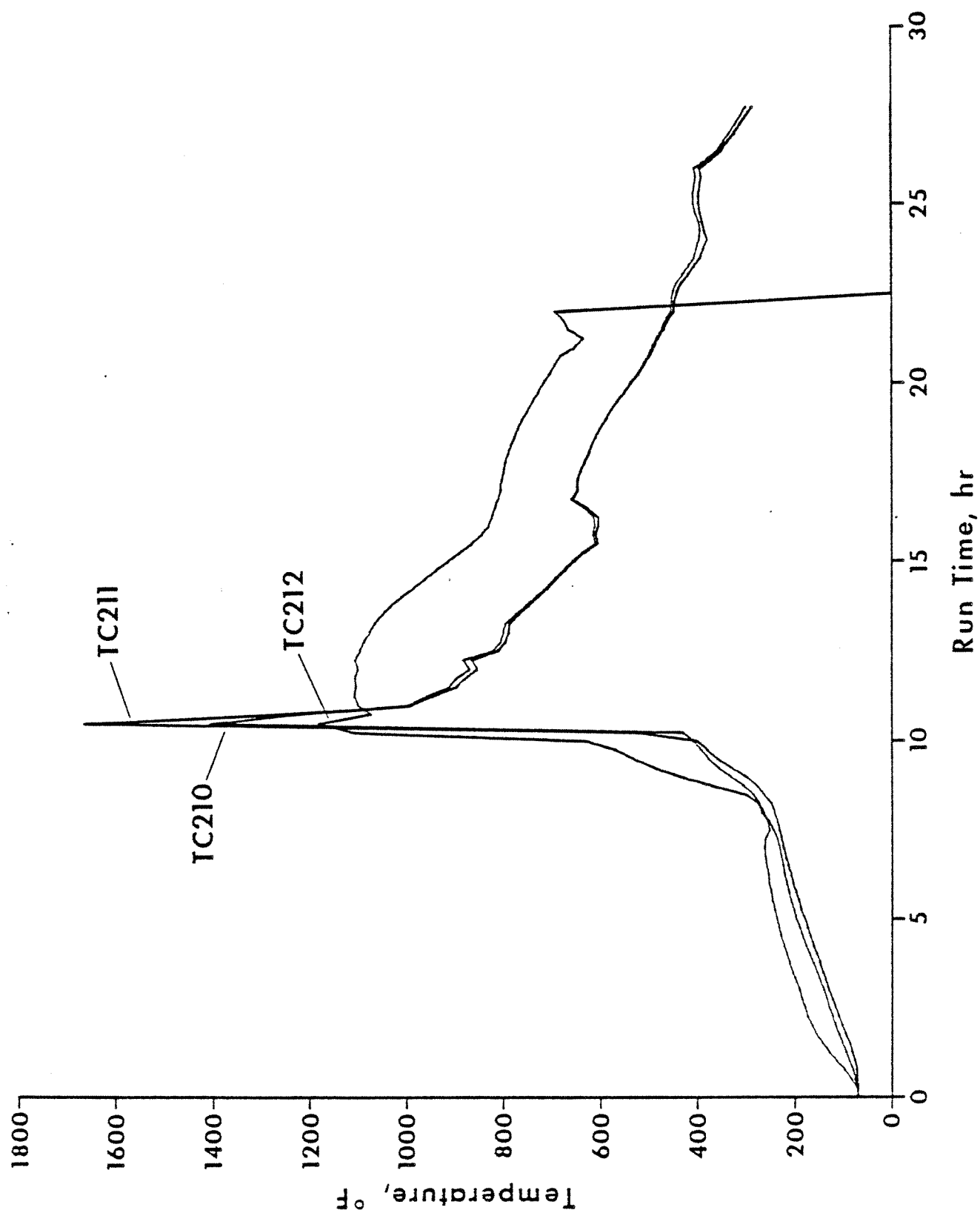


Figure 8. Process Temperatures for Asphalt Ridge Test BR16, Well M6

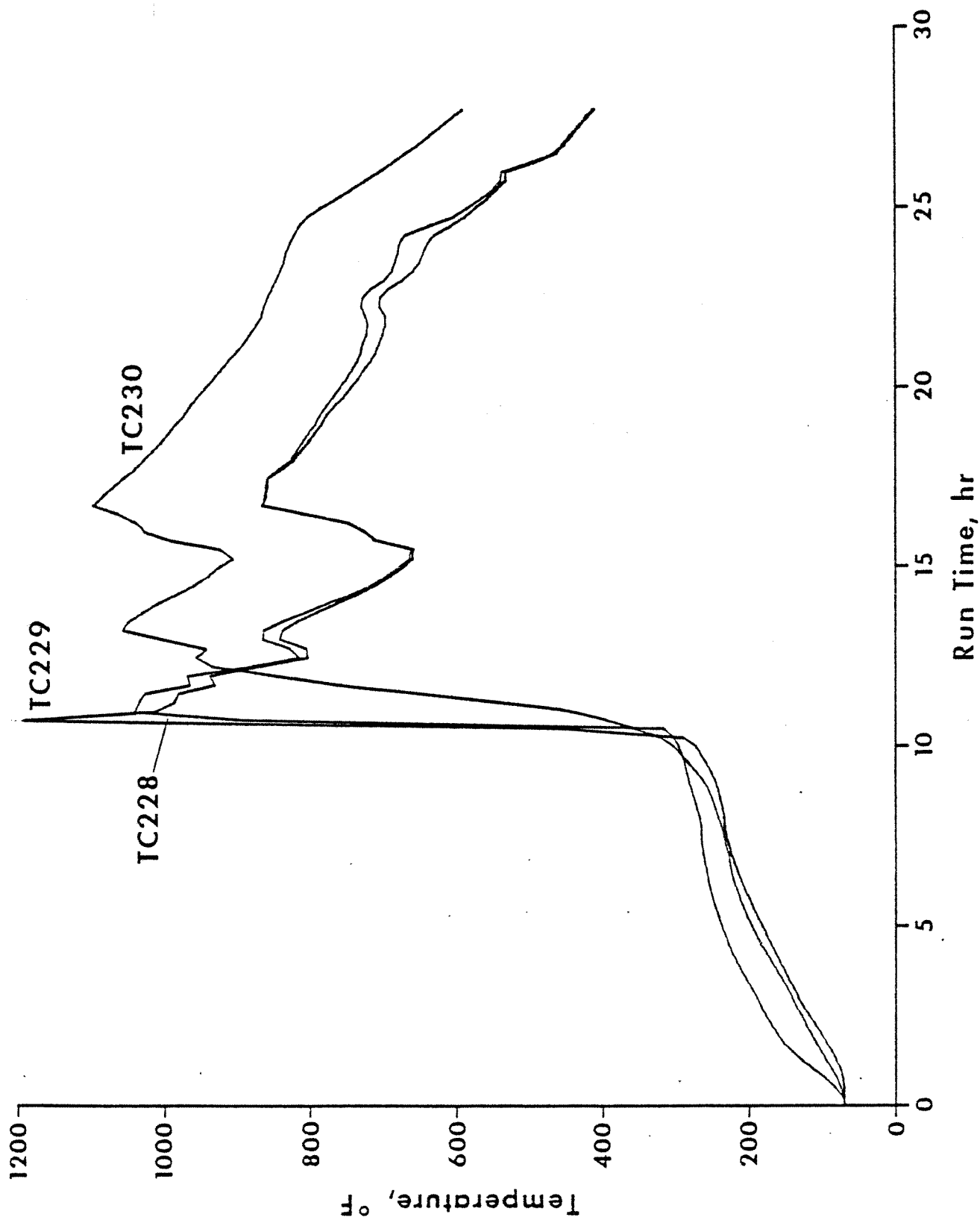


Figure 9. Process Temperatures for Asphalt Ridge Test BR16, Well M11

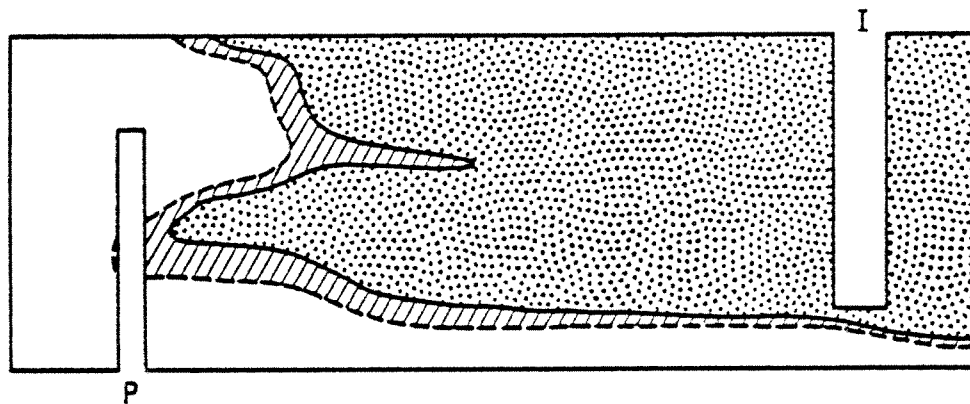
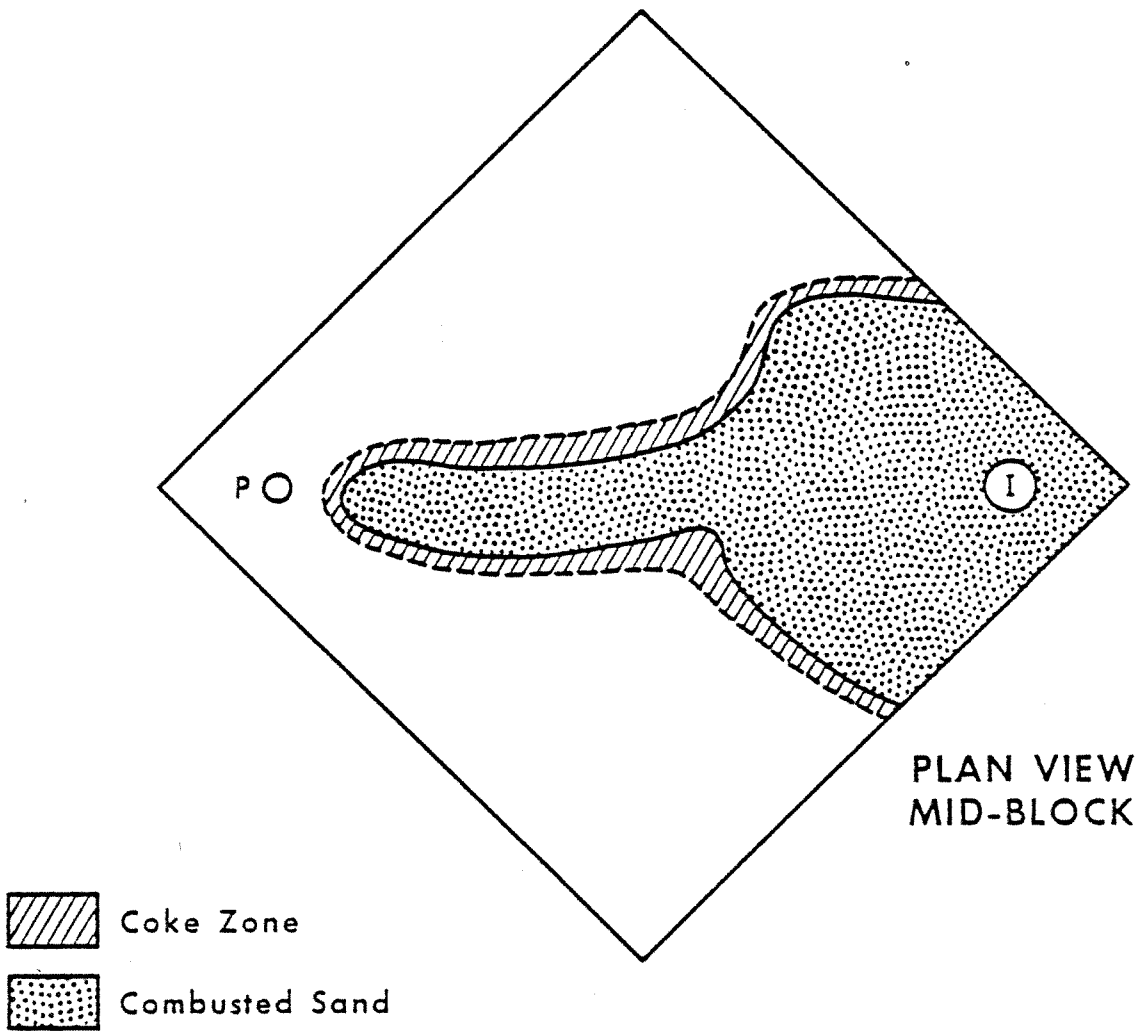


Figure 10. Process Sweep Configuration for the Asphalt Ridge Three-Dimensional Steam-Oxygen Forward-Combustion Simulation

occurred during the simulation as a gas-phase reaction which consumed product-oil vapors. Secondary cracking and combustion of product oil would decrease the oil yield, increase the calculated fuel deposition, and upgrade oil quality. All of these items are discussed later.

Fuel deposition during BR16, as determined from the nonpyrolysis-produced gas composition and residual coke, was 56.9 wt % of the initial bitumen within the sweep area (Table 2). This value is five times higher than the 10.9 wt % fuel deposition of FC60, although FC60 was operated at nearly identical pressure and steam-oxygen ratio as BR16. This result tends to support the hypothesis that additional bitumen and/or product oils were swept into the existing heated channel and were directly combusted, pyrolyzed or cracked to produce additional fuel that had to be consumed before the front could advance.

The overall material balance for BR16 was 96.2%, slightly less than the 98.4% average for the one-dimensional simulations (Table 4). However, the carbon balance was 100.3% for BR16, higher than the average for the one-dimensional tests but fairly close to that for FC62 (Table 5). The oxygen and hydrogen balances were 96.2 and 84.7%, respectively. The oxygen, hydrogen, and to a lesser extent the material balances are all affected by the low water balance (Table 4). Water balances around the block reactor system are a problem since the castable refractory used to seal the samples can be a source or sink for water depending on the pressure and temperature of the sample-refractory interface. In this test, it appears that the refractory was a sink for injected water (steam). However, even with the low water and hydrogen balances, the carbon, oxygen, and sand balances indicate the acceptability of the test data.

The oil yield for BR16 was 41.3 wt % of the original bitumen from the sweep zone compared with an average of 83.5% for the one-dimensional simulations. Oil yield as percentage of Fischer assay was only 53.7, which indicates that a large portion of the pyrolysis oil was either consumed by oxidation or underwent secondary cracking during the test.

Product oil from BR16 was significantly upgraded compared with the original bitumen and even when compared with the one-dimensional product oils (Table 6). The molecular weight, viscosity at 100°F (38°C), and the percentage material boiling above 1000°F (538°C) were 320, 134 cp, and 12.8 wt %, respectively. These properties for the bitumen were 670-710, 59,000 cp, and 47.6 wt %. The molecular weight, viscosity, and 1000°F (538°C) plus boiling material ranged from 450 to 510, from 7,270 to 21,800 cp, and from 46.1 to 48.2 wt %, respectively, for the one-dimensional product oils. This production of a highly upgraded oil compared with the other product oils indicates that a large portion of the heavier components of the product oil was either pyrolyzed or cracked to produce lighter fractions.

This consumption of a portion of the produced oil should occur during an actual field test since a front advances as a series of fingers or channels and not as a uniform front. The amount of produced oil consumed would, therefore, vary depending on the degree of the homogeneity of the reservoir and the severity of channeling.

Results of this test showed the detrimental effect of channeling on the oil yield for the forward combustion process. The channeling may have resulted from either inhomogeneity of the reconstructed block or the ignition procedure used in the test. Inhomogeneity of the sample should have been minimized by the packing routine used for the block. However, the startup procedure for the block test, ignition followed by steam addition, was the reverse of that used in the one-dimensional tests. Since the one-dimensional tests did not exhibit channeling, the block test results tend to indicate that the establishing of an oil bank with steam prior to ignition may enhance the process sweep efficiency by minimizing channeling.

CONCLUSIONS

The following conclusions have been made from the results of the three one-dimensional and one three-dimensional simulations of steam-oxygen forward combustion using Asphalt Ridge tar sand.

- As the steam-to-oxygen ratio increases, the fuel deposition decreases.
- Product oil yield and combustion front velocity increase as the steam-to-oxygen ratio increases.
- Product oil quality is significantly improved compared with that of the original bitumen.
- Channeling of the combustion front increases fuel consumption and oxygen demand.
- Channeling of the combustion front reduces oil yield but increases oil quality because of secondary cracking and pyrolysis of product oil.

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